Soft X-Ray Resonant Scattering Resolves Nanoscale Magnetic and Chemical Heterogeneity

A new *in situ* technique to study magnetic structure has been demonstrated in a collaboration involving LBNL and IBM. The technique has high sensitivity to variations in both magnetization and chemical composition over very short distances and in very small sample volumes. This makes it an ideal probe for the studies at the 1-100 nanometer length scales that are relevant to ultra high density magnetic recording.

Ferromagnetic materials such as iron can have a net magnetic moment even in the absence of an applied field, making them valuable in technologies ranging from electrical power conversion to information storage. Understanding in detail how the magnetic moment is distributed spatially in ferromagnets, and how this distribution reverses in an applied field is thus of fundamental scientific and technological interest. Key elements here are “magnetic domains,” regions of roughly uniform magnetization that are separated by “domain walls.” During magnetization reversal, these walls shift in complex ways, altering the shape and orientation of the magnetic domains. Because the size of magnetic domains determines the information density in magnetic recording, improved recording density depends on finding ways to stabilize magnetic domains at smaller and smaller sizes. Unfortunately, as magnetic domain sizes shrink, they become increasingly difficult to study experimentally, even with the most advanced techniques. This is especially true of fundamental studies in which it is desired (a) to study the behavior of the domains while large external magnetic fields are applied and (b) to understand the underlying chemical and/or morphological structures (species segregation, crystalline grain boundaries, etc.) that influence the size of the domains. For example, magnetic force microscopy can be used to image magnetic domains indirectly via their surface “fringing fields”, but this technique is limited to about 10 nm in spatial resolution and cannot be used in a large magnetic field. Neutron scattering can measure average magnetic domain sizes down to 1 nm but is not sensitive to changes in chemical structure.

The new LBNL/IBM technique builds upon the traditional method of achieving high spatial resolution in thin films by observing the small-angle scattering of x-rays. By carefully choosing the energy of the incident x-rays so they interact preferentially with selected magnetic (or other) elements in ferromagnetic samples, the scattering from those elements is increased by as much as 1,000 to 10,000 times. This resonant increase, enhanced by the inherently bright soft x-ray beams at LBNL’s Advanced Light Source, enables the detection of scattering from the magnetic domains themselves. Further, since applied magnetic fields do not affect x-rays, the technique can be used *in-situ* throughout complete magnetization/demagnetization cycles.

In initial experiments, resonant scattering techniques were shown to offer several approaches to resolve magnetic and chemical heterogeneity. The effect of changes in the incident angle on scattering provides information on the characteristic length of these spatial variations. The effect of an applied field on the sample, which causes the average magnetization to trace out a hysteresis loop, can also via x-ray scattering at a fixed angle, reveal directly the evolution of magnetic domains during the reversal process. Comparison of data at different fields and energies allows the unambiguous resolution of scattering caused by chemical heterogeneity (grain boundaries), from that caused by magnetic heterogeneity (domains). A surprising result for the Co/Pt sample studied here is that the magnetic domains are 10 times larger than the polycrystalline grain size. Thus, magnetic energies, rather than crystalline microstructure, dictate the domain size in this sample, limiting the value of this material as a magnetic recording medium.

This high sensitivity to magnetic as well as chemical heterogeneity makes these resonant soft x-ray scattering techniques generally applicable to the study of a broad range of magnetic, and non-magnetic materials. The LBNL/IBM collaboration is now using these tools to study nanoengineered films designed to produce ultrasmall, stable magnetic domains. The strong resonant enhancements enable sensitivity to just nanograms of material. This, together with other attributes, allows these resonant soft x-ray scattering techniques to provide information that is complementary to that obtained by more traditional neutron scattering and magnetic microscopy techniques.

J. B. Kortright (510)486-5960, Materials Sciences Division (510)486-4755, E. O. Lawrence Berkeley National Laboratory.

J. B. Kortright, S.-K. Kim, G. P. Denbeaux, G. Zeltzer, K. Takano, and E. E. Fullerton, “Soft x-ray small-angle scattering as a sensitive probe of magnetic and charge heterogeneity,” Physical Review. B, **64**, 092401, (2001).